

Challenges in Manufacturing Large Solid Boosters

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Abstract India as a spacefaring nation has been stressing on low-cost access to space as a major objective while developing propulsion modules for launch vehicles. This chapter dwells in detail the history of solid motors developed for rockets and launch vehicles by India. India's maturity in design, development and operationalising large solid boosters for launch vehicle application is also given.

The development of S200 solid booster for GSLV MK III, the new generation vehicle, has been brought out in detail. A number of challenges like realisation of long S200 motor case segments to minimise segment joints and thereby reducing the inerts, casting of 100 T propellant within the penetrometric pot life of HTPB-TDI propellant, handling and transportation of heavy S200 case segments, infrastructure build-up towards propellant processing and assembly and testing of S200 motor and flex nozzle system are discussed in detail. S200 pyrogen igniter development and propellant properties evaluation are brought out along with the demonstration of thrust differential seen in the flight performance of the two S200 strap-on motors in LVM3-X mission. Pressure oscillations seen in S200 motor are compared with large segmented motors like P-230, RSRM etc., and elimination of thrust oscillation isolation system has been validated in LVM3-X mission. Future road map envisaged for solid motor system development is addressed with a focus to reduce the inerts in solid propulsion system.

Nomenclature

Acronyms

Al	Aluminum
AP	Ammonium perchlorate
ASLV	Augmented satellite launch vehicle

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C/C	Carbon/carbon
CTPB	Carboxy-terminated polybutadiene
EPDM	Ethylene propylene diene monomer
FDI	Fault detection and insulation
GEO	Geosynchronous transfer orbit
GSLV	Geosynchronous satellite launch vehicle
GSLV MK III (LVM-3)	GeoSynchronous Satellite Launch Vehicle mark 3
HEF-20	High-energy fuel 20
HTPB	Hydroxyl-terminated polybutadiene
INCOSPAR	Indian National Committee for Space Research
ISRO	Indian Space Research Organisation
MEOP	Maximum expected operating pressure
PBAN	Polybutadiene acrylic acid acrylonitrile
PM	Pitch minus
PP	Pitch plus
PSLV	Polar satellite launch vehicle
PVC	Polyvinyl chloride
RSR	Rohini Sounding Rocket
SLV-3	Satellite launch vehicle 3
TDI	Toluene diisocyanate
TERLS	Thumba Equatorial Rocket Launching Station
TOIS	Thrust oscillation isolation system

Symbols

I_s	Specific impulse
kN	Kilonewton
m	Metre
MPa	Megapascals
Q	Dynamic pressure
s	Seconds
T	Ton
φ	Diameter

1 Introduction

In 1962 India started off in a modest way in the space segment with an agreement signed by the Indian National Committee for Space Research (INCOSPAR) with the National Aeronautics and Space Administration (NASA) for meteorological studies on equatorial region using sounding rockets. Initially in 1963, the US rockets with solid motors were assembled and launched as sounding rockets (Nike Apache) from Thumba Equatorial Rocket Launching Station (TERLS), Thiruvananthapuram,

situated in Kerala at the southern tip of India. Later in 1965, an agreement was signed with SUD Aviation, France, for a know-how transfer to realise and launch Centaur sounding rockets. A number of sounding rockets with Centaur rocket motors were realised, assembled and launched from TERLS. Rocket motor RH-75 indigenously developed by India for sounding rockets was launched in 1967 from TERLS. In 1968, TERLS was dedicated to the United Nations by the Prime Minister of India, and from then on, starting from 1971, M100 rockets were launched from TERLS routinely. Parallely RH-125 and RH-200 motors were developed on indigenous propellant composition and added to Rohini sounding rockets family. This was followed by RH-300 and RH-560 rockets with solid motors. The Indian Space Programme was given a major thrust by design, development and successful launch of SLV-3, a four-stage (all-solid motors) launch vehicle which put Rohini satellite into orbit in 1980.

In 1992, this was followed by ASLV with additional strap-on solid motors for launching 150 kg class satellite. With rich experience gained in the SLV-3 and ASLV programme, Indian Space Research Organisation (ISRO) embarked on an ambitious programme to develop Polar Satellite Launch Vehicle (PSLV) to launch 1 ton class satellites in the polar orbit of 1000 km circular with a lift of mass of 292 T. PSLV envisaged a combination of solid and liquid stages with bigger solid booster, graduating from 1 m dia 10 T class of solid motors of SLV, ASLV, to 2.8 m dia 138 T solid booster. From 1994, PSLV became the workhorse vehicle of ISRO performing a number of successful and unique missions starting from polar to GTO missions. The GSLV, largely with PSLV heritage, has a lift-off mass of 412 T with combination of solid, liquid and cryogenic stages. It could place 2 T class satellite in GTO in 2002 to fulfil the communication needs of the country. The GSLV MK III, conceived as a heavy lift launch vehicle with lift-off mass of 630 T, being developed for launching 4 T class satellites in GTO has large 200 T solid motor as strap-ons. With the successful development and testing in ground as well in GSLV MK III–X mission as strap-ons, India has become the third country next to the USA and Europe (joint project Italy and France), to successfully develop and induct large solid booster with HTPB propellant for launch vehicles (Fig. 1).

2 SLV-3 All-Solid Launch Vehicle

The Rohini sounding rocket (RSR) solid motors, with polyvinyl chloride (PVC)-based plastisol propellant with lesser solid loading and comparatively lower performance in terms of energetics, were generally cast as free grains and subsequently charged into the rocket motor casing with an epoxy- or polyester-based charging resin. The development of solid motors for the SLV-3 programme called for case-bonded motors with energetic solid propellants which were in situ cast into the motor case. Figures 2 and 3 give details on the solid motors [1] of SLV-3 launch vehicle.

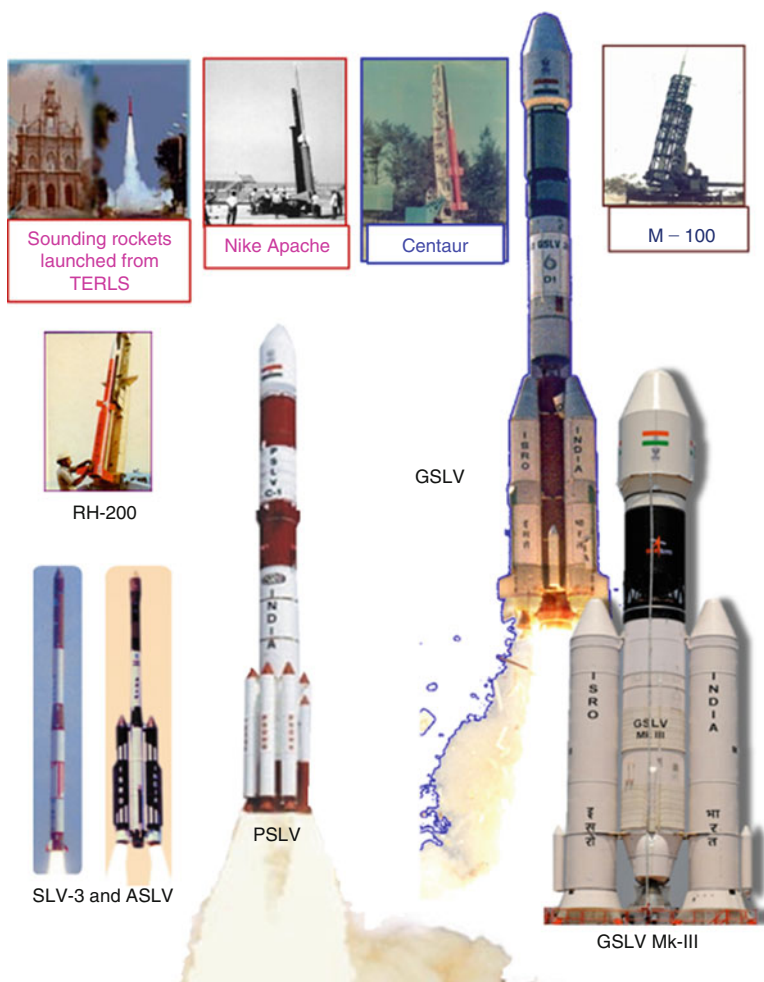


Fig. 1 History of rocketry in India

3 ASLV Motors

In the subsequent launch vehicle development, the PBAN- and CTPB-based propellant systems were replaced by hydroxyl-terminated polybutadiene (HTPB)-based propellant system which showed excellent mechanical, ballistic properties and superior performance. Table 1 on 1 m ϕ motor variants speaks for itself. The PS0M and PS0M-XL classes of 1 m ϕ motors with HTPB propellant have become the workhorse solid strap-on motors for PSLV in the operational programme, for a variety of missions with excellent track record. For the ASLV, AS0 motors with canted nozzle were realised with specific propellant formulations with faster burn rate in HE segment and slower burn rate in mid- and NE segments to modify the

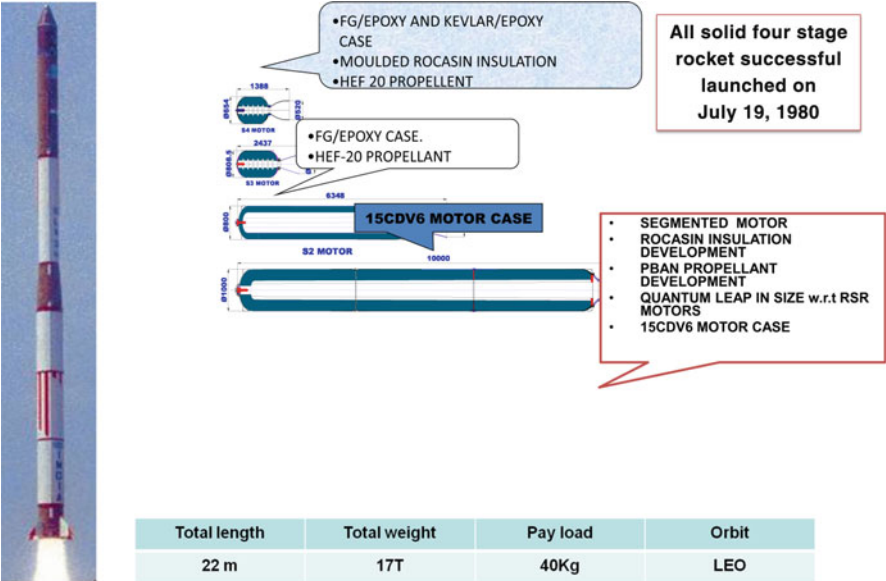


Fig. 2 SLV-3 all-solid launch vehicle

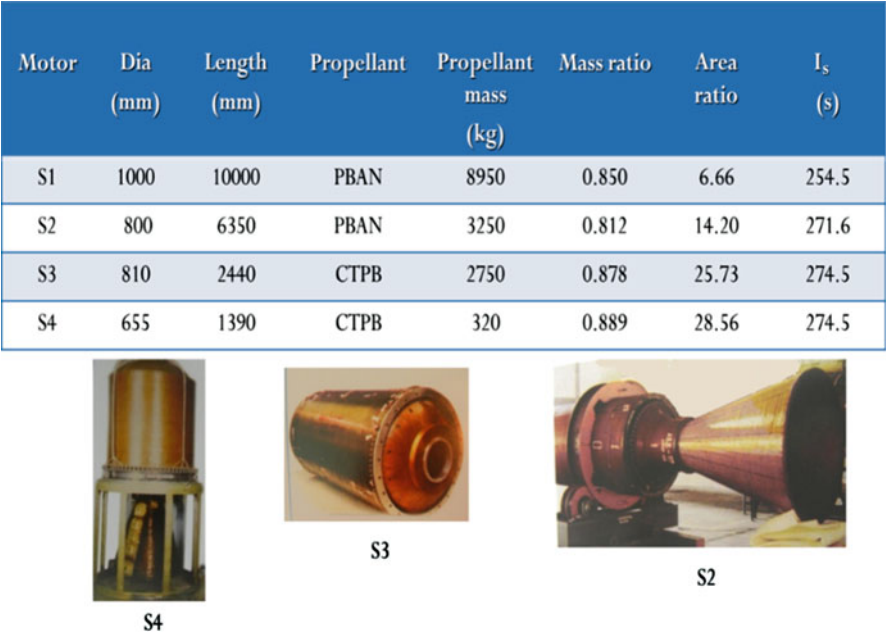


Fig. 3 SLV-3 solid stages description

Table 1 Variants of 1 m diameter motor – 1977–2010

	Propellant	Propellant mass, kg	Burn rate at 33ksc, mm/s	Burn time, s	I _s , s	Nos flown/tested
SI	PBAN/AP/Al	8660	4.8	45	253	6
ASO	PBAN/AP/Al	8637	4.8	45	253	7
ASO M type	HTPB/AP/Al	8520	5	45	259	7
ASI PBAN	PBAN/AP/Al	8900	5	45	259	4
ASI HTPB	HTPB/AP/Al	8915	5	45	262	2
PSOM	HTPB/AP/Al	8915	5	45	262	76
PSOM XL	HTPB/AP/Al	12400	5	50	265	8
RLV	HTPB/AP/Al	9100	3.7	90	255	1

All the motors tested at ground or flown consecutively were successful

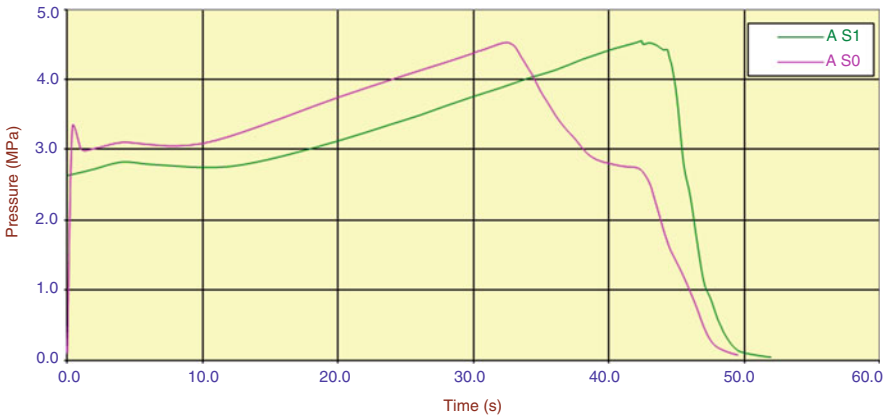


Fig. 4 Performance of ASI and ASO motors

thrust time profile of S1 motor. These motors were triple cast for confirming the pair motor identity for the strap-on motors for flight, by ground testing the third motor as batch motor for assuring the flight performance.

The first stage and second stage performance of ASLV was improved by replacing PBAN propellant (12 % Al) with HTPB propellant (18 % Al). Figures 4, 5, and 6 give the details of ASO and ASI motors and their performance.

Based on the experience gained in thrust shaping in ASO motor to contain the dynamic pressure (Q) during the transonic phase, the PSLV and the GSLV MK III solid boosters were designed with M-type thrust time curve by choosing a combination of star and cylindrical propellant ports for the boosters. The same approach was followed in the later improvements carried out on the PSO variant PSO-XL to enhance the propellant loading by 3 T and modifying the thrust time profile similar to M-type curve adopted in PSLV first stage motor. However, this M-type curve in PSO-XL motor is achieved by adopting cylindrical port at the head end and middle segments followed by combination of cylinder and star at the nozzle end

Fig. 5 ASLV launch vehicle**Fig. 6** Static test of AS1 motor

segment. Table 1 gives the details on 1 m dia variants developed by ISRO. Table 2 gives the comparison of PS0M and PS0M-XL motor with CASTOR-IVA-XL of the USA.

In the 1 m dia class of motors, different combinations of thrust time profiles was achieved to meet mission requirements. Though PS0M-XL and RLV SB motors adopt M-type thrust time profile, in view of Reusable Launch Vehicle (RLV) mission, HTPB propellant with retarder to give low burn rate has been chosen to meet the requirement for the RLV solid booster (RLV SB). Figure 7 gives the thrust time profile comparison of all the booster motors developed by ISRO for various missions.

Table 2 Comparison of 1m diameter motors

Sl. no.	Parameter	PSOM	PSOM-XL	Castor-IVA-XL
1	Propellant mass, kg	8915	12400	13000
2	Propellant	HTPB, 18 % Al	HTPB, 18 % Al	HTPB, 20 % Al
3	Action time, s	48.6	52.8	60
4	Vacuum I_s , s	262	264.5	269
5	Nozzle type	Canted, 9°	Canted, 9°	Canted, 11°
6	Grain configuration	6 point star	Cylindrical with 10 point star at nozzle end	Cylindrical with star at nozzle end
7	Area Ratio	6.42	7.57	15
8	Mass ratio	0.849	0.855	0.87

4 Overview of S200 Motor [2]

GSLV MK III (LVM3) is ISRO's third-generation launch vehicle capable of injecting 4 T class satellite into Geo Transfer Orbit (GTO). Paired strap-on S200 motors form the first stage of LVM3 and provide propulsive power for lift-off and ascend phase during the atmospheric regime of flight. S200 is configured as a three-segmented motor with 3.2 diameter and 22 m length. The motor has a flex nozzle and the motor ignition is achieved through a pyrogen igniter. The head end segment is 3 m long, whereas the mid- and nozzle end segments are about 8 m in length. Each S200 motor carries 207 T of HTPB propellant with a mass ratio of 0.89 and develops a peak thrust of 610 T. S200 motor delivers a specific impulse of 275 s (Fig. 8).

The head end segment has a ten-lobed star port geometry for the propellant grain, whereas mid-segment and nozzle end segments have tapered cylindrical grains. Segment ends are inhibited using castor oil-based inhibition system to prevent end burning. Silica-filled nitrile rubber-based material is used in the segments as thermal insulation. Motor case is fabricated with M250 maraging steel through roll and weld route and is designed to withstand a maximum pressure of 5.88 MPa. The three segments are assembled through tongue and groove joints.

The state-of-the-art submerged flex nozzle has an area ratio of 12. Nozzle vectoring is achieved by means of electro-hydraulic actuators powered in a blowdown mode.

4.1 Challenges in S200 Motor Development [3–5]

S200 motor has the largest motor case segment hardware manufactured in the world by roll and weld route (3.2 m Ø, 8.1 m and 8.3 m long mid- and nozzle end segments, respectively). The motor case hardware is proof pressure tested vertically with a floating piston arrangement for the nozzle end segment for simulating the throat open condition as in flight (Figs. 9, 10 and 11).

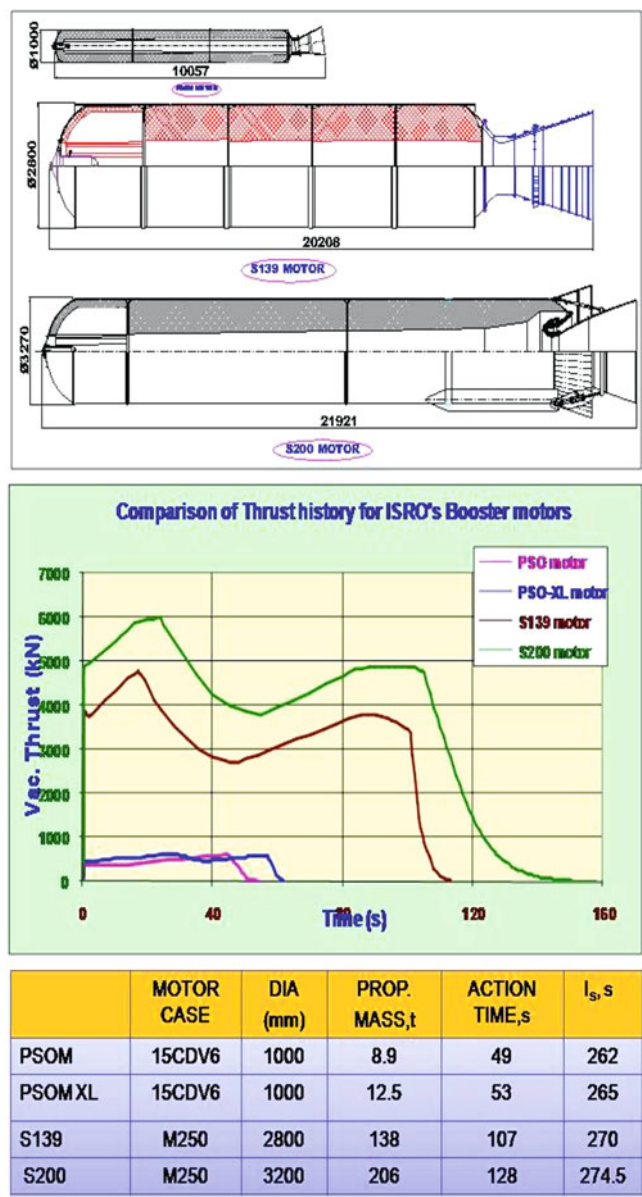


Fig. 7 Solid motors used currently as booster stage in ISRO

Processing of S200 motor involves major challenges like casting of 100 T propellant in single segment without defects, transportation and handling of segments as well as assembled motor at various facilities. Limiting the differential thrust between the strap-on S200 motors during GSLV MK III flight is achieved through

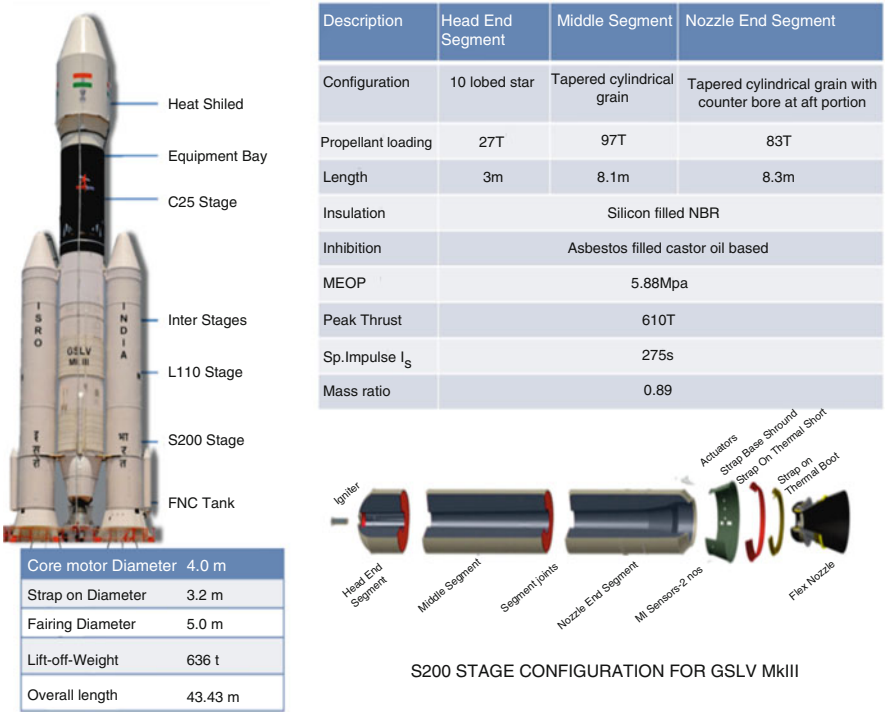


Fig. 8 GSLV MK III vehicle and S200 motor

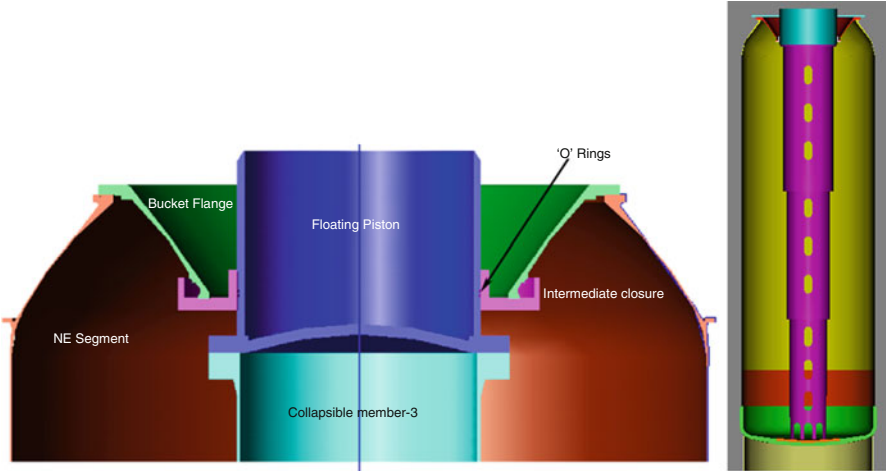


Fig. 9 Floating piston used in optimisation of motor case joints

Fig. 10 Hardware weld set-up

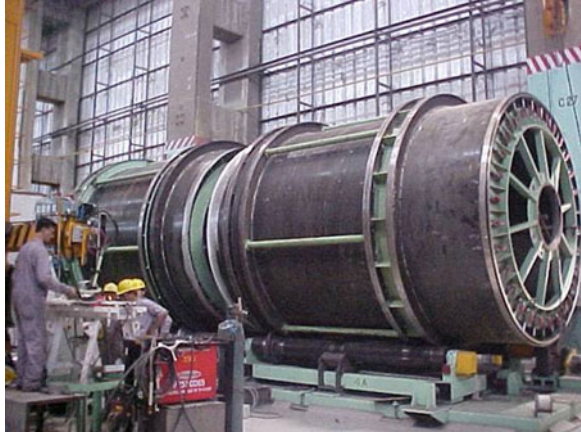


Fig. 11 Case PPT set-up



matched pair concept. Key propellant raw materials are chosen from the same batch for propellant processing of the strap-on motor segments. Thrust profile is shaped appropriately so as to achieve a gradual thrust fall rate during tail-off phase.

The sequence of operations, in composite propellant processing right from raw material preparation to propellant finishing operations, is given in Fig. 12.

Major facilities established for processing S200 motor include five mixing stations so as to process and cast the 100 T propellant within the penetrometric pot life of the propellant. A casting station with bowl tilting mechanism, sample

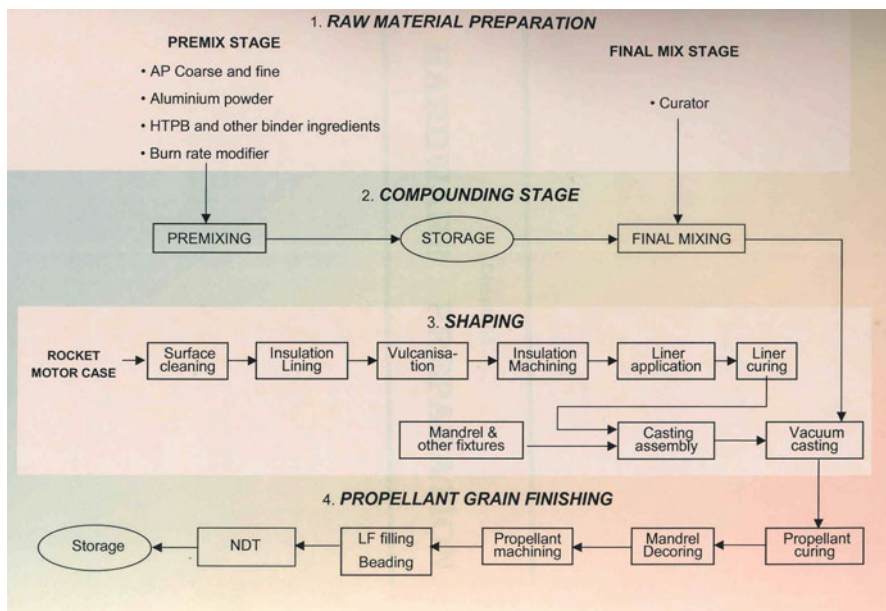


Fig. 12 Sequence of operations in propellant processing

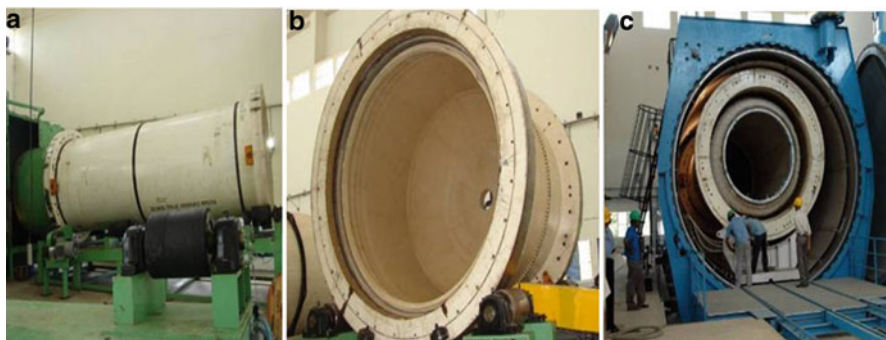


Fig. 13 **a** Blast cleaning machine. **b** Insulation lining on roller. **c** Insulation vulcanisation in autoclave

processing facility, curing oven, propellant machining and NDT facility were built for manufacturing the large S200 booster motor. Curator toluene diisocyanate (TDI) batching is introduced during propellant mixing to avoid manual intervention during the operation. Automated spill collection tray is provided at the mixing station to collect propellant slurry from the mixer blades. For hardware preparation and insulation lay-up, a facility for blast cleaning, degreasing and insulation lining and a 4 m diameter autoclave were installed (Figs. 13, 14, 15, 16 and 17).



Fig. 14 Spill tray collection system

Fig. 15 TDI batching



Fig. 16 2.5 T-mixer



A centralised control centre is established for synchronised propellant mixing and dispatch for casting. The earlier concept of change can converted to continuous casting by incorporating master hopper and continuous slurry transfer. Master hopper, slurry transfer systems, a feed control involving automatic control valve

Fig. 17 Control system room**Fig. 18** Manufacturing challenges for large solid motors

and weighing systems for segment were procured for the new casting facility for realising S200 segments. Fabrication and transportation of 7 m diameter and 15 m long vacuum chamber weighing more than 130 T and producing a defect free 100 T segment with high casting rate of 4.5 T/h were some of the challenges faced during the development phase of S200 motor. Semiautomated slurry collection and bowl cleaning were established to reduce manual intervention and to adhere to safety standards. Propellant specimen preparation and sample processing facility is established with automation to reduce manual work load. During material processing, symsorting of ammonium perchlorate (AP) is introduced by identifying same batch for pair segments. Hydraulic tilting system for tilting 100 T segment and introduction of C-arm tackle or grabber for vertical handling of segment have minimised human intervention during propellant processing. Figures 18, 19, 20, 21 and 22 give details of manufacturing challenges during the development.

Fig. 19 Change can type casting



Fig. 20 Continuous casting with master hopper



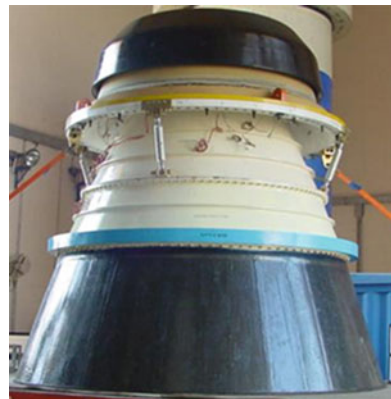
Fig. 21 Vacuum chamber during transportation

New facilities for drying, classification and blending for augmenting the production of ammonium perchlorate (AP) are established. AP recovery plant is established to recover AP from the process effluent. Indigenous AP grinder is developed for producing AP fines.



Fig. 22 Segment being lowered into casting pit

Fig. 23 Flex nozzle 12 AR



The flex nozzle is processed as five subassemblies utilising modular concept. The flex seal employed is the second largest in the world and enables vectoring of the nozzle up to 8° . The elastomer formulation has been tailored to achieve low shear modulus to bring down actuation torque. The flex seal is made through compression moulding. The nozzle liners in pair strap-on motors are parted from a single liner block to avoid differential performance. Electro-hydraulic actuators used with the flex nozzle are of 30 T capacity with fault detection and isolation (FDI) scheme inbuilt into the control electronics (Figs. 23, 24 and 25).

A thin-webbed igniter grain is made with modified technique of introduction of intermittent vibration during casting to ensure the absence of grain defects. Figures 26, 27 and 28 give the features of S200 igniter development.

After realising the S200 motor, the ballistic performance needs to be evaluated through static test. The quality of the motor is confirmed through various methods. During the initial design stage, the master stress relaxation curve and the failure boundary curve for the finalised propellant formulation are evaluated. The basic

Fig. 24 Moulded flex seal
(dia 1700)



Fig. 25 30 T
electro-hydraulic actuator



Fig. 26 S200 igniter grain

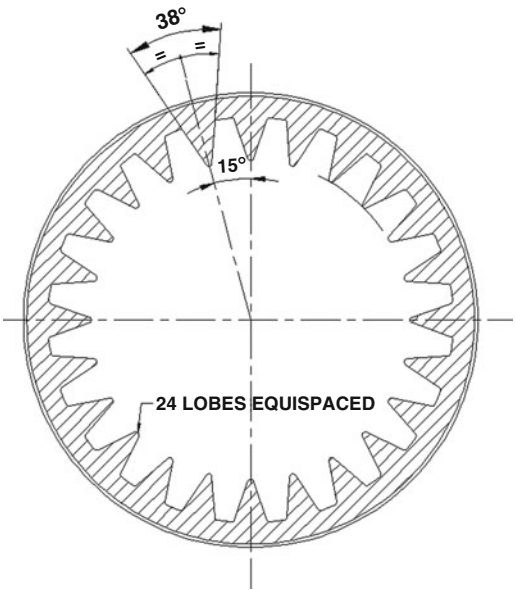


Fig. 27 S139 igniter grain

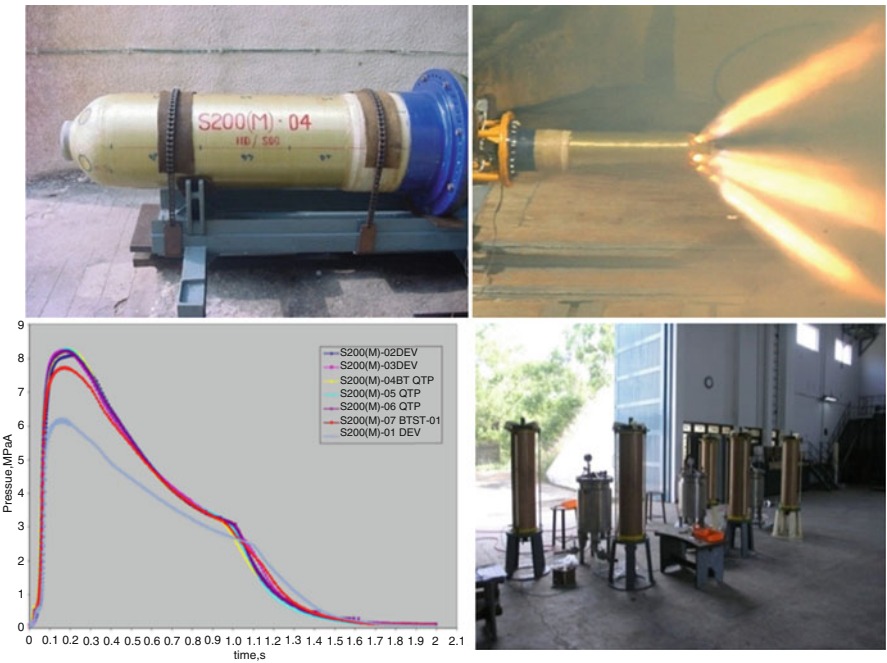
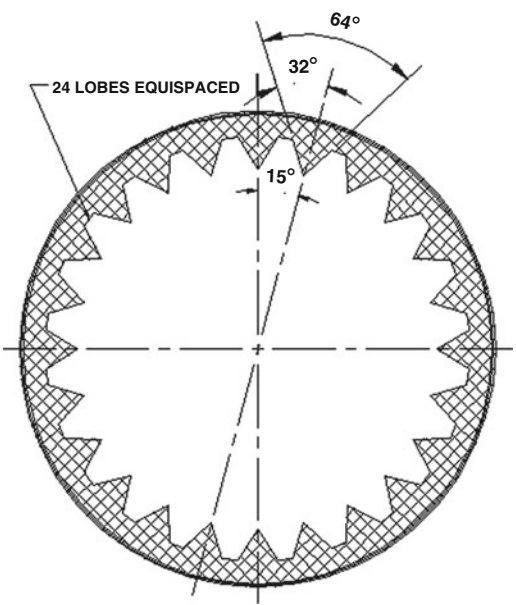


Fig. 28 S200 igniter development

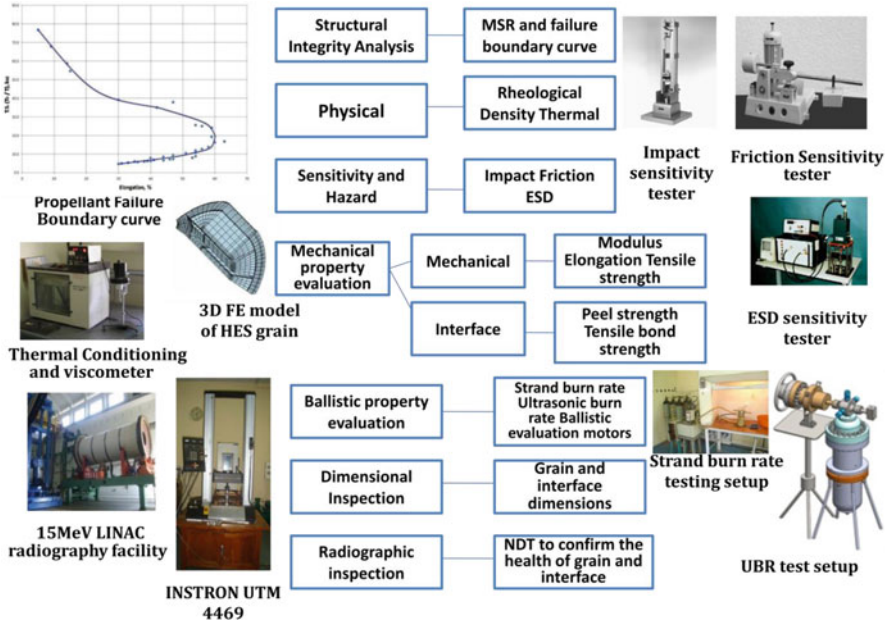


Fig. 29 Evaluation of propellant properties

physical, mechanical and interface properties of the propellant are evaluated to provide inputs for structural analysis of the grain. Then the structural analysis of the cast segments is carried out to confirm the margins on the grain and at the interfaces. The ballistic properties of the propellant are evaluated through solid strand burn rate, through ultrasonic burn rate and through ballistic evaluation motors. The dimensions of the grain at the interface and at the port are measured to confirm the interface requirement for integration as well as for ballistic performance prediction. Finally, the soundness of the grain and the interface integrity are evaluated by radiography (Fig. 29). During the propellant processing and realisation of the S200 motor, manual intervention is minimised to the maximum extent and good safety procedures are put in place to make this large solid propellant plant a safe working place.

After confirming the quality and health of the motor, the segments and the subsystems like flex nozzle and igniter need to be assembled together. New facilities for vertical integration of the motor and for trial actuation of the flex nozzle are built. Facilities for static test are augmented to meet the testing requirements of the S200 motor. Two static tests are successfully carried out demonstrating the identical performance of the two S200 motors. The recent successful GSLV MK III–X mission with two S200 solid boosters as strap-ons has demonstrated the pair motor performance and differential thrust in the flight (Figs. 30 and 31).

Table 3 gives the performance of S200 flight motors in LVM3–X mission. Table 4 gives comparison of S200 motor with contemporary boosters.

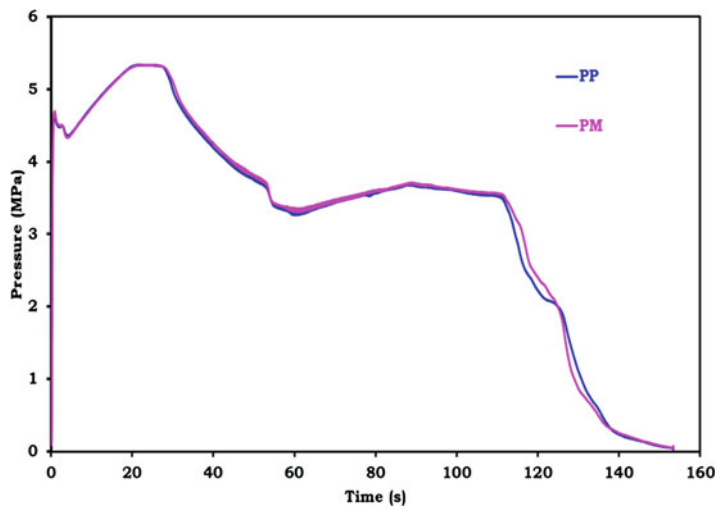


Fig. 30 Performance of S200-X-PP and PM motors

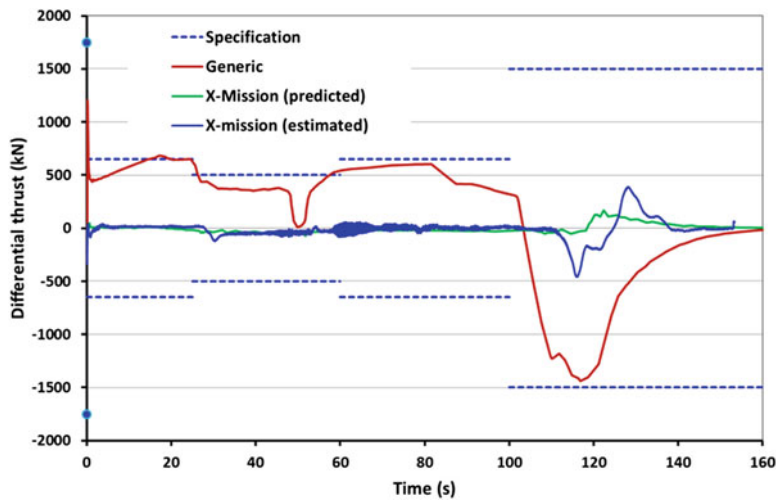


Fig. 31 Differential thrust measured during flight

5 Pressure and Thrust Oscillations [7, 8]

As observed in other contemporary motors like P230 and RSRM, pressure and thrust oscillations were observed during the two motor ground tests and in LVM3-X mission flight as well. The oscillations are mainly due to the coupling of the vortices formed due to the protrusion of the left out segment joint inhibition into the port to

Table 3 Performance summary of S200 motors in flight

Parameter	S200-X-PM	S200-X-PP
Burn time (s)	111.6	111.3
Action time (s)	134.5	135.5
Maximum pressure (MPa)	5.332	5.334
Pressure integral (MPa-s)	498.2	495.6
Maximum vacuum thrust (kN)	5770.6	5788.5
Average vacuum thrust (kN)	4138.9	4102.6
Vacuum specific impulse (s)	276.7	276.2
Total impulse (MN-s)	561.5	559.9
Max. differential thrust, kN	459	

Table 4 Comparison of S200 motor with large solid boosters [6]

	RSRM	SRMU	P230	SRB-A	S 139	S200
Motor launcher	Shuttle	Titan 4B	Ariane IV	H II A	PSLV	MK III
Diameter (m)	3.7	3.2	3.0	2.5	2.8	3.2
Motor length (m)	38	31	27	12	20	19.3
Propellant mass (tons)	503	314	240	65	138	207
Binder	PBAN	HTPB	HTPB	HTPB	HTPB	HTPB
Segment	4	3	3	1	5	3
MEOP (MPa)	7.0	8.4	6.8	11.8	5.88	5.88
Case material	D6AC	Carbon	D6AC	Carbon	Maraging Steel	Maraging Steel
Throat material	Phenolic	Phenolic	C/C	C/C	Phenolic	Phenolic
Actuation	Flex seal	Flex seal	Flex seal	Flex seal	Liquid	Flex seal
	Hydraulic	Hydraulic	Hydraulic	EMA Electromechanical actuation	Injection	Hydraulic
Motor inert mass (tons)	68	29	29	6	18	25
Stage inert mass (tons)	88	36	36	11.5	30	30
Average thrust (MN)	11.8	6.1	5.0	1.8	3.6	3.64
Specific impulse (s)	267	284	275	280	269	275

the motor acoustic modes. The disturbances due to vortices will grow at frequencies near to the acoustic mode of the combustion chamber.

Table 5 gives the comparison of the pressure oscillation of S200 motor with the boosters elsewhere in the world.

The thrust to pressure oscillation amplitude ratio is estimated as 14 % for design purposes after removing the damping provided by the thrust measurement system. The frequency of pressure and thrust oscillations are similar even though their occurrence is not simultaneous. The pressure/thrust oscillation begins after the

Table 5 Comparison of oscillations observed in S200 motor with contemporary motors

Motor	L (m)	Dia (m)	Seg	Inhib (yes/no)	Inter-seg cavity	Burn time (s)	Acou modes	Freq (Hz)	Dp/p (%)	Time (s)
P230	25	3.05	3	Yes	Yes	129	1	18–23	0.5	60–110
							2		0.2	40–80
							3		0.1	~50
RSRM	35	3.8	4	Yes	Yes	123	1	12–15	0.48	110–115
							2	25–30		
SRMU	32	3.2	3	No	Yes	138	1	15–20	0.27	57–64
PS1	16.5	2.8	5	Yes	No	100	1	27	0.3	45–72
							2	33		72–94
S200	19.5	3.2	3	Yes	No	105	1	21–26	1.3	40–110

burnout of the HE segment and continues till the burnout of the motor. The effect of inhibition thickness on the amplitude of oscillations is demonstrated in the two ground tests. Higher thickness of the inhibition results in deeper protrusion into the flow and stronger oscillations and vice versa. Thrust oscillation isolation system (TOIS) proposed earlier was later dispensed with based on the studies conducted with the measured pressure and thrust oscillations in the S200 ground tests. LVM3-X flight has been flown successfully without TOIS.

6 Future Road Map for Solid Motors [9]

Future road map envisages performance improvement by improving the motor/stage mass ratio. Focus will be on the following aspects:

- Segmented composite motor case with higher pressure capability to be developed to reduce the inert mass of the motor case and nozzle by reducing the throat diameter as well as improve the area ratio.
- Fifteen to 20 % reduction in insulation mass when nitrile rubber is changed to ethylene propylene diene monomer (EPDM)-based rubber.
- Composite flex seal shims in place of metallic shims to reduce the mass of flex seal and to avoid thermal boot and hence reduce the torque requirement for vectoring.
- The hoop stress component on the FNC tank can be shared by the composite overwrap. This will help in reducing the mass of the gas tank to the extent of 35 %.
- As the stress on the divergent hardware is very minimal, the material of construction can be changed to aluminium alloy.
- Un-submerged flex nozzle system offers advantage of minimal spring stiffness where an electromechanical actuator is sufficient to vector the nozzle. Electromechanical actuation system has an advantage of minimum prelaunch activities and minimum movable parts as compared to electro-hydraulic system.
- High energy and green propellants are the next options for improvement in specific impulse and minimal effect on the environment.
- Extensible exit cone for upper stages to accommodate higher area ratio nozzle within the available space.

7 Conclusion

The successful development of the family of large solid boosters of ISRO for various missions has demonstrated its capability and maturity in solid motor design and solid propellant technology. The technology is totally homegrown and indigenous.

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